

EFFECT OF POLYMER ADDITION AND SURFACE ALTERATION ON FLOW OF FLUIDS THROUGH POROUS MEDIA

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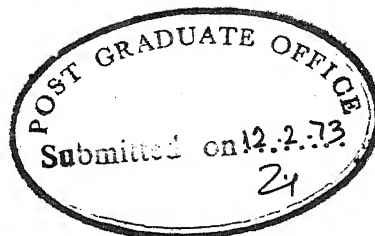
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CERTIFICATE

This is to certify that the present work, "Effect of Polymer Addition and Surface Alteration on Flow of Fluids Through Porous Media" has been carried out under my supervision and that this has not been submitted elsewhere for degree.

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ABSTRACT

In the present study, the effect of altering the surface characteristics by coating the glass surface with silicone oil, and addition of polymer (polyox) on flow of fluids through porous medium was investigated.

In the single phase flow study, polymer solutions of different concentrations were passed through a pack of clean as well as silicone oil coated glass beads. At any flow rate the pressure drop was found to increase with concentration of polyox in water due to viscoelastic effects and adsorption of polymer. The decrease in apparent viscosity, calculated from the flow of fluid through the pack of silicone oil coated beads, compared to that for clean glass beads was explained on the basis of a corresponding decrease in adsorption due to surface coating.

Kerosene and water were used for two phase flow studies.

Radio-active tracer technique was employed to measure saturation of water which was tagged with Cs^{137} .

Two phase relative permeability measurements were made both on clean glass bead pack and silicone coated glass bead pack to study the effect of wetting. Measurements were made both during imbibition and drainage to show the effect of saturation history.

(Polyox addition to water in two phase flow study resulted in reduction of the relative permeability to both the kerosene and water phases. But higher reduction in relative permeability to waterphase made kerosene phase more mobile at all values of saturation.)

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LIST OF SYMBOLS

A	Area of cross section of flow
A_w	Adhesion tension of water
A_o	Adhesion tension of oil (kerosene)
k	Specific permeability of the porous medium
k_w	Effective permeability to water
k_o	Effective permeability to oil (kerosene)
k_{rw}	Relative permeability to water
k_{ro}	Relative permeability to oil
l	Length of the packed bed
ΔP	Pressure Drop across packed bed
q	Volumetric flow rate
s	Saturation of the packed bed
T	Tortuosity of the packed bed
t	time
\bar{V}	Average superficial velocity
η	Viscosity of a liquid
ϕ	porosity of the packed bed
$\dot{\gamma}$	Shear rate
γ	Surface tension of a liquid
θ	Contact angle
\bar{d}	Average pore diameter

CHAPTER I

INTRODUCTION

The study of flow of multiple phases of fluids through porous medium is basic to such diverse fields as petroleum reservoir engineering, chemical engineering, soil science, and ground water hydrology. The secondary recovery of oil from petroleum reservoir by gas drive, water or polymer solution flooding, the seepage of water in sands displacing air in the process and the flow of gas and liquid in packed absorption columns are some of the well known examples of the application of multiple phase flow of fluids through porous media.

The wide range of applications holds out varied ways to carry out research work into fundamental as well as field problems. However, in multiple-phase flow the distinction between miscible fluid phases and immiscible phases along with the regime of flow, i.e., whether the flow is laminar, turbulent, molecular etc., cuts across, to some extent, many diverse fields in presenting a coherent picture.

As can be intuitively realized, the properties of porous medium and of fluids characterize the flow. The interaction of fluids with surfaces give rise to adsorption and interfacial tension. Because of complexity of porous

medium, thermodynamic approach towards the forces at play in liquid-solid or liquid-liquid interface is not useful. To overcome this, the concept of wettability which is a consequence of capillary forces has been successfully applied in the study of simultaneous flow of immiscible fluids. If a system of fluid 1, fluid 2 and solid 3 forms a line of three phase contact and if at this line of contact the planes tangential to the 1/2 and 1/3 interfaces enclose an angle θ , less than 90° , then the fluid 1 is called wetting phase and fluid 2, the nonwetting phase. It is difficult to observe contact angles in a porous medium but the concept of wettability has a relative meaning in so far as of two fluids, the preferentially wetting one will penetrate into a porous medium against a less wetting one.

The variety of experimental procedures to measure wettability can be grouped into three heads. The first type of wettability measurements, proposed by Bartell and Osterhof(1), consists in measuring minimum displacement pressure to force one fluid against another fluid saturating the pack. This minimum pressure, termed 'threshold pressure', is used to calculate the contact angle. Modification of this has been employed by Singhal (2) to measure threshold pressure under dynamic conditions.

In the second category can be included 'imbibition tests' where the rate of displacement of the original saturating fluid

by imbibition of a second fluid, gives a measure of wettability. Moore and Slobad (3) and Bobek et.al. (4) have devised suitable apparatus for this purpose. Crawl et al (5) have calculated the contact angle from the data based upon the unopposed penetration of a liquid through a bed of powder.

The third type of measurement - fractional wettability - consists in determining the fractions of the internal surface microscopically wettable by the two fluids. The fluid wetting the highest fraction of the internal surface is said to wet the solid. Brown and Fatt (6) used a nuclear magnetic relaxation method and Holbrook and Bernard (7) a dye absorption to determine wettability.

In the present study, imbibition test as carried out by Crawl et al (5) was selected to determine wettability. This choice was made because of the simplicity of the experimental set-up.

As has been pointed in the 'theory', relative permeability is a concept based upon the extension of Darcy law to multiple-phase flow. The laboratory techniques, used for the measurement of relative permeability of porous media may be grouped into two classes: (1) capillary pressure methods (2) dynamic methods. Hassler (8) developed capillary pressure method which has been modified by Gates and Lietz (9), Brownscombe et. al (10) and Osoba et.al. (11). The main feature of this method consists in controlling the capillary pressure at

both ends of the sample by placing the porous material between two discs permeable only to the wetting phase.

The second group or dynamic method allows all fluid phases to flow through simultaneously and the pressure difference is measured some distance away from the ends to eliminate end effects. Here, determination of saturation is difficult as compared to that in capillary pressure methods.

Since saturation is associated with relative permeability much effort has been expended in perfecting techniques to measure this parameter. They include the gravimetric method, the electrical conductivity method (12, 13, 14), the x-ray adsorption method (15, 16, 17), radiation emissions from tracer dissolved in the fluids (18, 19, 20), neutron bombardment (21) gamma-radiation attenuation (22, 23, 24, 25, 26), diminution and phase shift of ultrasonic wave trains (27, 28) magnetic susceptibility (29), neutron defraction (30), and magnetic resonance (31, 32, 33).

General discussions and reviews of Pen state method, Hassler method, single sample dynamic method, stationary liquid method, gas drive method, Hafford and dispersed feed method that are applied to measure relative permeabilities have been given by Browncombe et al (34, 35, 10), Rose (36, 37) Osaba et al (11), and Richardson et.al. (38). All these methods use gravimetric technique to determine saturation in the porous material. This necessitates the interruption of the test

after each flow measurement to determine the weight during which losses of fluid by evaporation may occur. In certain saturation range, removal of porous material from the flow assembly causes as much as 10% of the pore space (39) liquid to be expelled.

The electrical conductivity method (12,13,14) suffers from the inherent defect that the resistivity of a rock partially saturated with a conducting fluid is not only a function of saturation but also of the special distribution of the fluid which, in turn, depends upon the wettability and on the saturation history.

The nuclear magnetic resonance technique is very suitable (31,32,33) to measure fluid saturations in two phase and especially in three phase relative permeability studies. However, the n.m.r. equipment was not available at the time of this study, hence radio-active tracer technique was employed which is also suitable for twophase relative permeability studies. The flow of non-Newtonian fluids through porous medium has been the subject of vigorous investigations in recent years. The major thrust, in most part of these studies, is directed towards unravelling the reason why the flow of viscoelastic fluid through porous medium differs significantly from the flow through capillary. In other words, the viscosity calculated from capillary or any standard viscometer, cannot account for the large pressure drop for flow of even dilute viscoelastic

fluid through porous medium. Bird, Stewart and Lightfoot (40), Christopher and Middleman (41), and Gaitonde and Middleman (42) have extended the analysis of Ergun (43) for flow of Newtonian fluids through porous medium to purely viscous non-Newtonian fluids. Usual power law formulation was employed to describe the non-Newtonian properties of the fluids used. Viscoelastic effects are also pronounced in porous medium as the flow through this is always unsteady from Lagrangian point of view. Deborah number, defined as the ratio of duration of fluid memory to the duration of deformation process, is a measure of viscoelastic effects. Marshall and Metzner (44) have defined the conditions under which Deborah number may become large to cause more pressure drop for viscoelastic fluids flowing through porous media under noninertial conditions. According to this analysis which idealizes the porous medium as consisting of diverging and converging cones major effects may be produced at Deborah number in the range 0.1 to 1.0.

Dauben and Menzie (45) have concluded that the permeability reduction for polyethylene oxide solutions in porous media is the result of anomalous viscosity effect and the interaction of polymer macromolecules and the matrix. However, it has been proposed by Gogarty (46) that the reduction of permeability is a result of differential plugging effect. In constant pressure experiments, Sadowski (47) experienced difficulties

which did not crop up in constant flow rate experiments. This observation led to the analysis that during constant pressure experiments gel formation would be aggravated because of less tendency to remove polymer molecules from the particle surface. In constant flow rate experiments the constant fluid motion would prevent a gel net work from forming between particles. Thus the concept of a mechanical entrapment or pore blockage effect is strongly supported by Sadowski's investigations. Burick (48) reasons that the shear thickening behaviour observed in the flow of dilute polymeric solutions through porous media is a consequence of polymer molecules being retained within the pore structure. These bound molecules are uncoiled under the applied high velocity gradient, thereby increasing the resistance to flow.

Another interesting observation is that some dilute polymeric solutions cause a decrease in permeability of the porous medium to other Newtonian liquids that follow the flow of polymer solution. Jennings et al (49) have investigated this behaviour of different polymer solutions in porous medium.

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CHAPTER II

THEORY

The theory of laminar flow of homogeneous Newtonian fluids through isotropic porous medium is based on Darcy's law

$$q = - \frac{kA}{\mu} \text{ Grad } P \quad (1)$$

where q is the volumetric flow rate, k is the specific permeability characteristic of porous medium and is independent of the nature of fluid, A is the area of cross-section of flow, μ is the viscosity of flowing fluid, and $\text{Grad } P$ is the gradient under which the flow is taking place. When gravity effect is neglected or eliminated $\text{Grad } P$ becomes applied pressure ΔP over a length l of the porous medium. By postulating that the Darcy's law is valid for each flowing phase of immiscible fluids, there results two modified Darcy equations, one for kerosene (oil) and the other for water. These two equations are:

$$\begin{aligned} q_o &= - \frac{k_o A}{\mu_o} \frac{\Delta P_o}{l} \\ q_w &= - \frac{k_w A}{\mu_w} \frac{\Delta P_w}{l} \end{aligned} \quad (2)$$

The subscripts o and w denote oil and water phases respectively. k_o , and k_w are termed the effective permeabilities to the

respective phases and $\frac{\Delta P_o}{l}$, $\frac{\Delta P_w}{l}$ are the pressure gradients in the respective phases and are different because capillary forces act differently on different fluids due to wettability characteristics of the porous medium to the two fluids.

Now define a term relative permeability as the ratio of effective permeability of any flowing phase to the specific permeability of the medium.

$$k_{ro} = \frac{k_o}{k}, \quad k_{rw} = \frac{k_w}{k} \quad (3)$$

where k_{ro} and k_{rw} stand for relative permeabilities to oil and water respectively. Substitution of equation 3 in equation 2 gives

$$q_o = \frac{k_{ro} k A}{\mu_o} \frac{\Delta P_o}{l} \quad (4)$$

Substituting, once more, k from equation 1 and rearranging, we obtain

$$k_{ro} = \frac{q_o \mu_o}{q \mu} \left(\frac{\Delta P}{\Delta P_o} \right) \quad (5)$$

By definition specific permeability is a rock property and is independent of the fluid flowing through it, μ and ΔP could be made the same as μ_o and ΔP_o respectively. So

$$k_{ro} = \frac{q_o}{q} \quad (6)$$

i.e. relative permeability of oil is the ratio of the rate of flow of oil when other fluids are present to the rate of flow

of fluid when only that fluid is present. Since q_o is a function of saturation,

$$k_{ro} = f_o(S_o) \quad (7)$$

By similar analysis $k_{rw} = f_w(S_w)$

Equations 6 and 7 imply that relative permeability is independent of viscosity and pressure gradient and is substantiated by experimental results. Some of the limitations of the generalized Darcy law for multiple phase flow are due to the same causes as the limitations of the Darcy law in single phase flow, such as adsorption, molecular slip, turbulence etc. Rate of fluid flow has been shown (50, 51, 52) to have no effect on relative permeability till inertial effects become important. Owing to the occurrence of hysteresis in wettability the same phenomenon must occur in relative permeabilities. Thus it can be safely concluded that relative permeability is not a unique function of saturation but depends upon the saturation history of the porous medium. This has been substantiated by earlier workers (21,39).

There are two effects related to the capillary pressure phenomena, or wettability, that are important from experimental point of view. One is called the 'end effect' or 'boundary effect' which exists at the effluent end of the porous medium because of discontinuity in the capillary properties of the system. The wetting phase fluid concentration increases at the

outlet face causing error in saturation measurements. The end effect is eliminated or minimized by increasing pressure gradient which renders capillary forces relatively unimportant. The other method to eliminate end effect consists in taking the measurements at some distance away from the end where boundary effects are negligible. Studies by Richardson et al (38) and Geffen et al (39) show that beyond a length of 2 to 4 cms. from the outflow face the end effects do not normally exist.

The second important observation is that the relative permeability of the non-wetting phase depends upon its own saturation as well as the saturation of the wetting phase and the relative permeability of the wetting phase is dependent only on its saturation and is independent of other non-wetting phase saturations (53).

The concept of capillary models has been applied to the treatment of the theory of relative permeability by various workers, Rose (54, 55), Rapport et al (56), Fatt et al (57) Burdine (58), and Naar et al (59, 60). However, a universal model of relative permeabilities could not be arrived at mainly due to the complexity of the porous medium.

It has been stated that relative permeability is independent of viscosity and pressure gradient. However, this does not hold good in case of polymeric solutions due to anomalous viscosity effects arising out of viscoelastic property and also due to the adsorption of polymer on the porous matrix.

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CHAPTER III

EXPERIMENTAL SET-UP

1. Saturation Determination:

Radio-active tracer technique was employed to determine the saturation of two immiscible phases, water and kerosene, in percentage pore volume of the porous medium. The equipment to measure saturation was a gamma ray detector. The scintillation detector unit was made up of a scintillation head (type SH 635), a low voltage unit (model LV 230A), and a high voltage unit (model HV 200). The above instruments were procured from Trombay Electronic Instruments, Bombay. The signal from the scintillation head was fed to an assembly unit having a universal spectrometer (model 401), and a Universal ratemeter (model 231). These equipments were supplied by the Tracer Lab., U.S.A. A schematic diagram of the complete unit is shown in Figure 1.

Cesium chloride (Cs^{137}Cl) was used as a tracer which was soluble only in the water phase and not in kerosene. Known amount of cesium chloride was added to water. The scintillation detector sensed the amount of the isotope salt present in the porous pack which was proportional to the water saturation.

The packed bed, whose saturation was to be determined, was placed before the scintillation head at a particular position

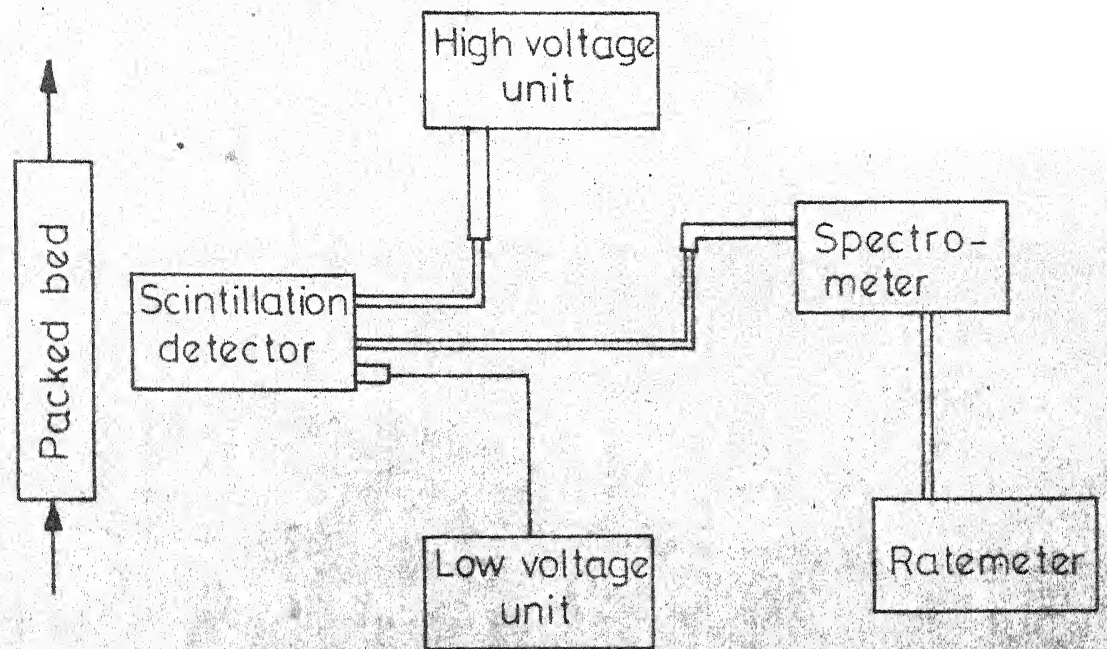


Fig. 1 - Schematic diagram of the Gamma-ray detector unit.

during the period of calibration and saturation determination. This precaution of placing the packed bed only at a particular position before the scintillation head excludes any error creeping in because of distance effect. First a calibration was made to find out the relationship between the activity of the tracer, in volts and percentage saturation of water in the porous medium. The procedure of calibration has been detailed in next chapter. This calibration curve enabled the measurement of water saturation in the multiple phase flow.

2. Flow System for Immiscible Fluids:

A schematic diagram of the set-up for the flow of the two immiscible fluid phases, water and kerosene, is shown in Figure 2. Constant head bottles were used to deliver constant flow rate, necessary to maintain steady state. The two fluids were passed through a mixer before flowing through the packed bed. The other parts of the set-up are self explanatory from the Figure.

The flow rates of water and kerosene at steady state were measured by collecting the fluids in a measuring cylinder for known amount of time.

3. Measurement of Pressure Drop Across the Packed Bed:

The pressure difference across the packed bed was measured by a differential transducer, Tavis Decuder (mod.4-100).

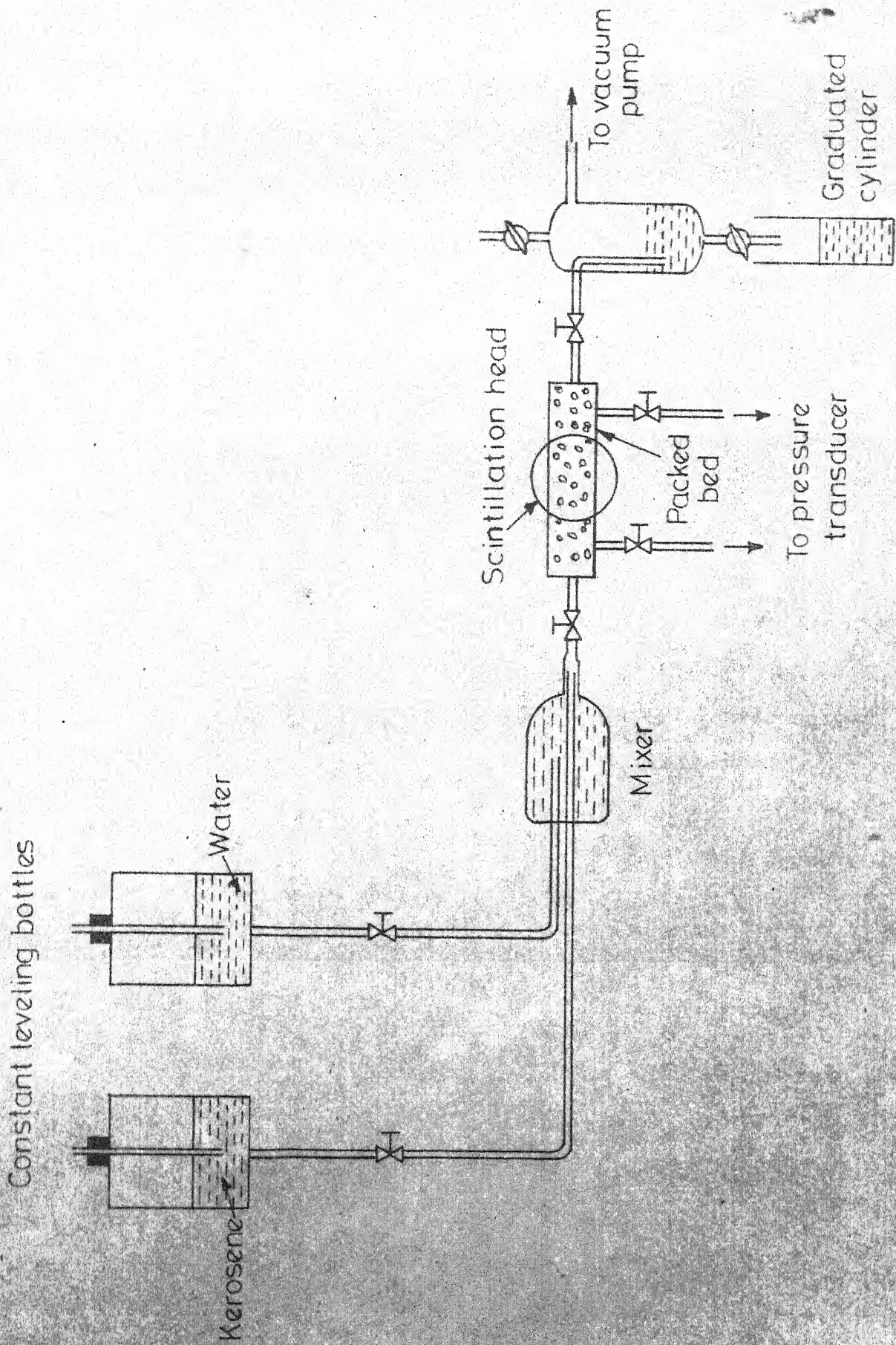


Fig. 2 - Experimental set-up for the flow of immiscible fluids.

The input excitation of 27 VDC at 25 ma was supplied by dry cells or a regulated power supply, made by Aplab (type MV 5/10).

The output voltage responding to the pressure differential, caused by the flow of fluids, was fed to a DC micro volt-ammeter (model 425A), procured from Hewlett-Packard Company of U.S.A.

4. Measurement of Wettability:

Capillary rise technique was employed to evaluate the wettability of the pack of glass beads. Glass beads, whose wetting characteristics were to be determined, were placed in a graduated glass tube of 1 cm diameter, the diameter of the tube being sufficiently large to eliminate wall effects. A screen at the lower end of the tube kept the glass beads in position. The packing was done by tapping as this method of packing has been reported to be most satisfactory by Crowl et al (5). The packed bed was dipped into a dish of liquid and the liquid rise into the packed bed was noted down against time. The wetting characteristics for glass beads were calculated as given in Appendix A.

5. Materials Used:

The glass beads (micro spheres), used to make packed bed, were in the size range of 210 to 297 microns (-50 to + 70 mesh). These glass beads were supplied by Lapine Scientific Company, Illinois, U.S.A.

The silicone oil (L-45 silicone), used to coat the glass beads, was manufactured by Union Carbide Corporation, Chemicals and Plastics Division, New York.

Distilled water was one immiscible phase. The other phase was straight run kerosene, boiling range 140-300°C, supplied by Barauni Refinery.

The radio-active tracer which tagged the water phase was Cs^{137} Cl having a half life of 30 years, was procured from Isotope Division, Atomic Energy Establishment, Trombay, Bombay.

The polyox (polyethylene oxide), used to prepare polymeric solutions, was water soluble (WSR 301), supplied by Union Carbide, Chemicals and Plastics Division, Union Carbide India Limited.

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CHAPTER IV

EXPERIMENTAL PROCEDURE

Sample Preparation:

The glass particles were cleaned by washing them thoroughly with Acetone (AR grade) followed by immersion in hot chromic acid for 18 hours. The acid traces were removed by rinsing the particles with distilled water for a number of times.

To study the effect of change in wetting characteristics the glass beads were coated with silicone oil in the following manner. Silicone oil, 0.5% by weight of glass beads, was dissolved in A.R. grade acetone. The clean glass particles to be coated, were poured into this solution and the slurry was thoroughly stirred to ensure uniform coating on the glass particles. The beads were left immersed over a sufficient time for complete adsorption of silicone oil on the surface. The excess liquid was drained and acetone was evaporated at room temperature. Dried particles were found to be completely nonwetting to water as confirmed by imbibition test. To remove this surface coating the glass beads were heated to their annealing temperature (61).

Calibration:

As has been mentioned earlier, the packed bed was placed before the scintillation head at a fixed position during the

calibration
and saturation determination to eliminate distance effect.

It was observed that the tracer, Cs^{137}Cl , gets adsorbed on the glass beads. So the activity of the water, tagged with the tracer, Vs. saturation of the porous medium could not be plotted for the purpose of calibration. To overcome this, AlCl_3 was added in small amounts. This AlCl_3 was preferentially adsorbed on the glass surface and helped in cutting down the tracer adsorption on the glass. The small activity of the tracer adsorbed on the beads, was set aside as back-ground noise.

A stock solution of water with radio-active tracer, Cs^{137}Cl , and AlCl_3 was prepared for the two-phase flow study. Samples of this solution were taken and diluted to different concentrations with respect to tracer by adding fresh water. For example, 10 parts of tracer tagged water added to 90 parts of fresh water constituted a solution whose activity is 10% to that of the stock solution. Hence the activity of this solution in porous medium can be regarded as that of a packed bed having a saturation of 10% of the stock solution and 90% of kerosene. The packed-bed was completely saturated with such a solution by first evacuating it and subsequently flooding it with the solution. The activity was noted down from the ratemeter reading. The packed bed was emptied of the solution and again reading of the activity was noted down. This procedure was repeated for solutions of various concentrations. The result

has been shown in Figure 3. The increase in activity of the saturated bed represents the activity of the radio-active tracer tagged water. The background noise corresponds to the activity of the empty bed arising out of the adsorption of the tracer on the glass beads.

Flow Measurements:

The packed bed was saturated with tracer tagged water as described above. This liquid was passed through the bed at different flow rates and the corresponding pressure drops were measured with the help of the transducer. Permeability of the pack was computed from these data.

For two-phase flow study, the porous medium was saturated with water* and this liquid was made to flow as in single phase study. The kerosene was introduced in the packed bed at a low flow rate which was gradually increased to higher value until the water stopped flowing. The flow rate of water was, then, increased, in steps, until the kerosene stopped flowing through the porous medium. Flow rates, and the pressure drops were measured at various points of saturation history of the bed as summarized in Appendix B. All these readings were taken at steady state as ensured by the constancy in flow rates.

*Water in two phase flow study implies the stock solution of $AlCl_3$, the radio-active tracer and water.

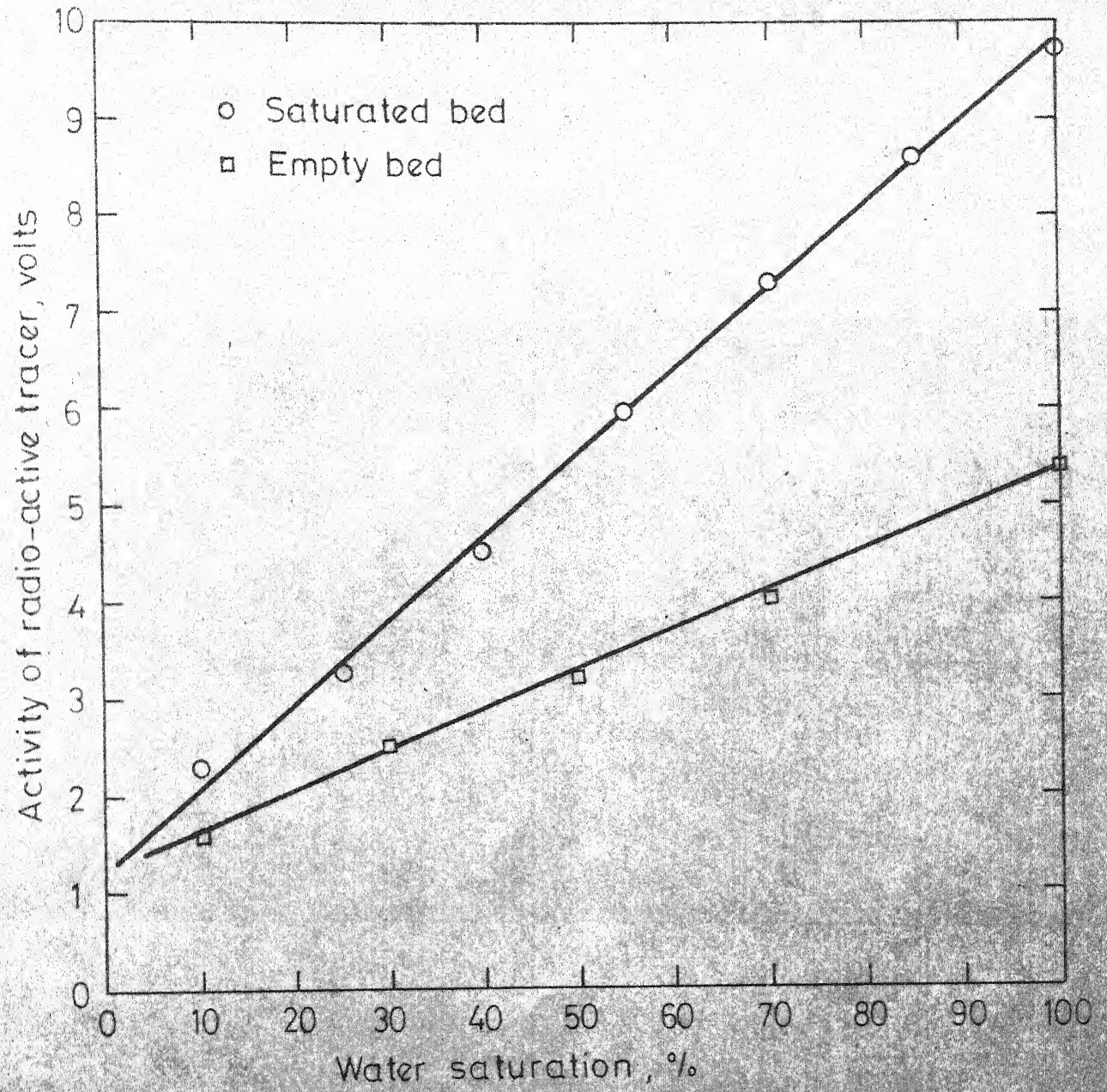


Fig. 3 - Calibration curve for saturation determination of porous medium.

Similar procedure was adopted for the study of two phase flow of fluids through silicone oil coated beads*.

Before the study of polyox solution and kerosene through porous medium, a single phase experiment of flow of polyox was undertaken both for clean glass beads and silicone oil coated beads. Solutions of 10 ppm, 25 ppm, 50 ppm, and 100 ppm polyox in water were used in this study. Flow rates and corresponding pressure drops were measured. The experimental procedure, adopted in the flow of polyox (100 ppm) and kerosene, was the same as that of water and kerosene. The saturation, flow rate and pressure drop data are given in Appendix D.

*The results have been tabulated in Appendix C.

CHAPTER VI

RESULTS AND DISCUSSION

a. Flow of Dilute Polymer (Polyox) Solution Through Packed Bed:

The pressure drop across packed bed of cleaned glass beads is plotted against flow rate of water and polyox solution of various concentrations as shown in Figure 4. The packed bed was 1.05 cms in diameter and 12.35 cms in length and the glass particles were in the size range of 210-297 microns. The porosity of the bed was 0.36 as calculated from gravimetric method. The flow of water obeys Darcy's law upto a flow rate of 30 mls/min which corresponds to a modified Reynolds number of 4 based upon the average diameter, 250 microns, of glass particles. Numerous investigators (62, 63) have studied this range of flow rate for which laminar flow exists. The transition from laminar to turbulent flow occurs in the range of Reynolds number from one to ten. At high flow rate the slope of the curve for water constantly increases because of inertial effects and turbulence. In the case of polyox solution, the pressure drop at any flow rate increases with an increase in the concentration of polyox in water. Again, for polyox solutions, the pressure drop is linear at low flow rates. As this flow rate increases the pressure drop falls below the linear relationship. This is possibly because of the degradation of

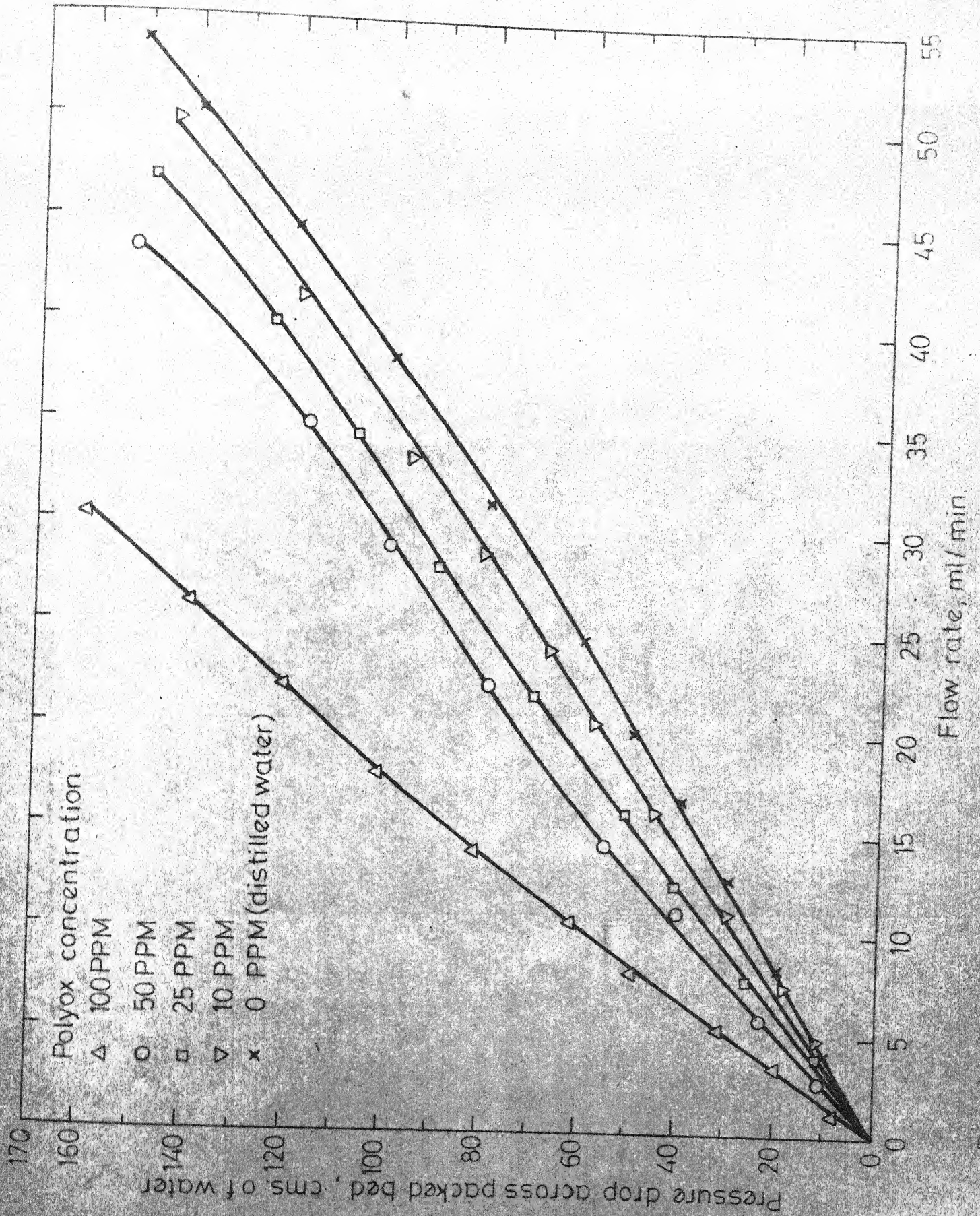


Fig. 4—Effect of polymer concentration on pressure drop across packed bed of clean glass beads.

of polyox at high shear rate when the long chains of this high molecular weight polymer, primarily responsible for viscoelastic effects, are shear degraded.

Figure 5 shows the pressure drop plotted against the flow rate for packed bed of glass beads coated with silicone oil. In this case, the transition from laminar region starts around a modified Reynolds number of 4.5 for water flow. The pressure drop, for polyox solutions, at any flow rate also increases with an increase in the concentration of polyox solution as is the case for clean glass beads. Again the degradation of polyox at high shear rate lowers down the pressure drop.

To study this phenomenon of large pressure drop created by dilute polyox solution, the apparent viscosities (Darcy viscosities) of 100 ppm polyox solution were calculated from flow measurements through pack of clean glass beads and silicone oil coated beads. The flow of pure water was taken as the basis and the Darcy's equation was used for this calculation. Figure 6 shows the apparent viscosity of 100 ppm polyox solution vs shear rate for silicone oil coated and clean glass beads. The shear rate was calculated employing the equation

$$\dot{\gamma} = \frac{\bar{V}}{\left[\frac{1}{2} (k/\phi) \right]^{1/2}}$$

Where $\dot{\gamma}$ is the shear rate, \bar{V} is the average superficial

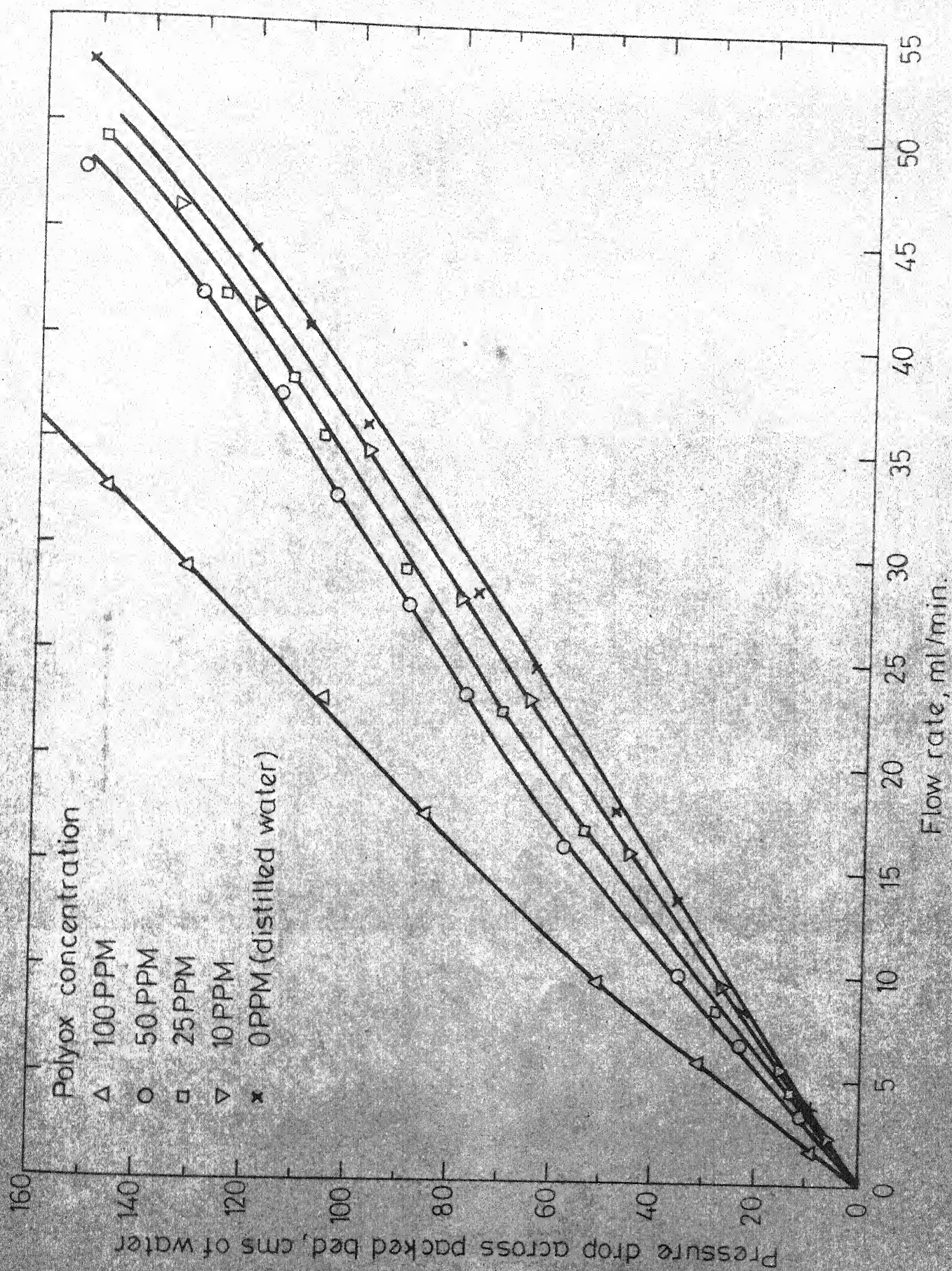


Fig 5 - Effect of polymer concentration on pressure drop across packed bed of silicone oil coated glass beads.

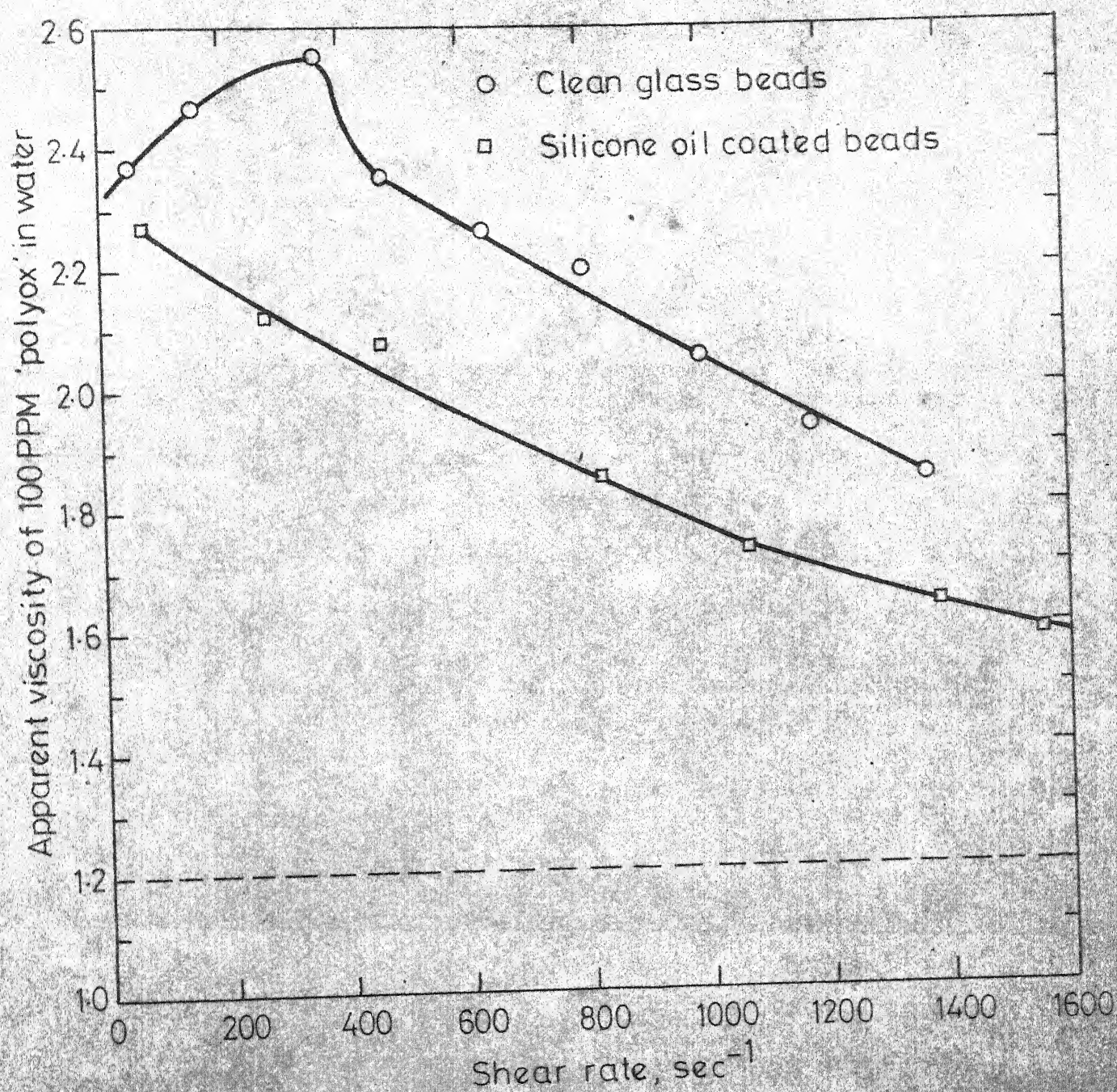


Fig. 6 - Apparent viscosity of 100 PPM polyox vs. shear rate.

velocity, k is the permeability of the bed, and ϕ is the porosity. The derivation of this equation is given in appendix E. For clean glass beads the apparent viscosity increases with shear rate upto a value of 370 sec^{-1} beyond which the continuous decrease in apparent viscosity sets in due to shear degradation. The apparent viscosity for silicone oil coated beads is lower than that for cleaned glass beads. This decrease shows the effect of coating only, fluid dynamic conditions remaining essentially the same, and this decrease can be reasoned out only in terms of corresponding decrease in adsorption or mechanical entrapment of polymer in porous matrix due to coating of silicone oil. Gogarty (46) has concluded that the increase in viscosity or the reduction of permeability is a consequence of adsorption of polymer. That the apparent viscosity is different due to coating confirms this conclusion of adsorption of polymer. Capillary viscometer study (45) has given the viscosity value of 100 ppm polyox solution to be 1.2 cp and fairly independent of shear strain. The apparent viscosity for both coated and cleaned beads is much higher than this value. The existence of viscoelastic effects has been reported by a number of investigators to explain this phenomenon (44) but little effort seems to have been made to isolate the effect due to adsorption and the viscoelastic effect.

b. Studies of Two Phase Flow of Immiscible Fluids Through Packed Bed:

The relative permeability vs. water saturation for a pack of clean glass beads is shown in Figure 7. Water was the wetting phase as confirmed by wetting test, detailed in Appendix A. The relative permeability to water phase is considerably lower than that to kerosene phase at their respective saturations. For example, at 70% water saturation the relative permeabilities to water phase are 0.285 during drainage and 0.39 during imbibition. At 70% kerosene content, corresponding relative permeabilities to kerosene phase are 0.86 and 0.68. This is understandable since water, being wetting phase, adhere to the glass beads forming films and kerosene being nonwetting phase forms bigger channels through which it can move more freely. At very high water saturation this continuous network for kerosene is broken and the permeability to kerosene reduces to zero. Similarly at very high kerosene saturation the relative permeability to water phase becomes zero. The hysteresis of relative permeabilities for both the kerosene and water phases is also shown in this Figure. This hysteresis is a result of a number of stable distributions of fluids at a given saturation depending upon the saturation history.

Figure 8 shows the relative permeability vs. water saturation for glass particles coated with silicone oil. Water

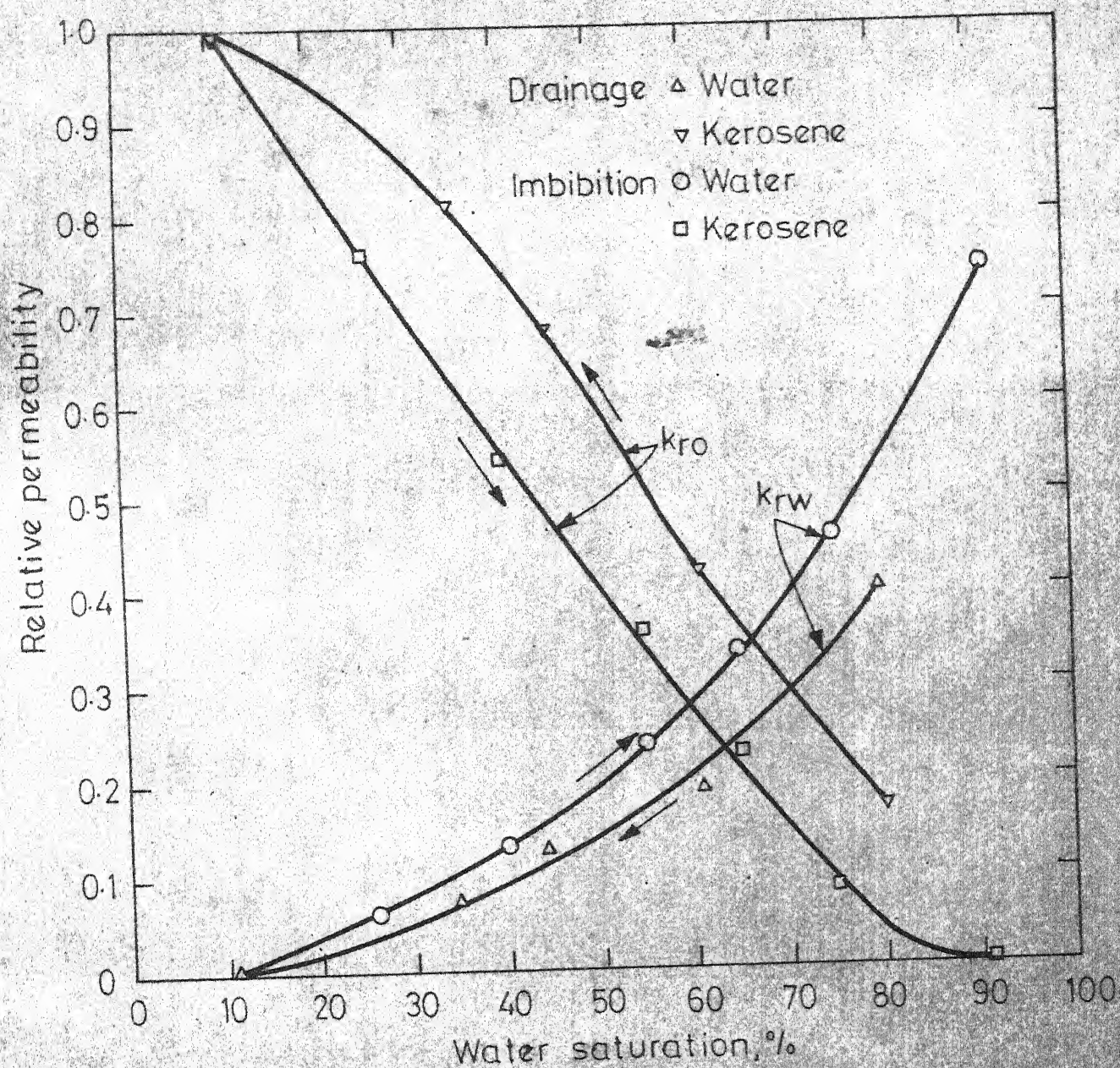


Fig. 7 -Relative permeability vs. water saturation for glass particles.

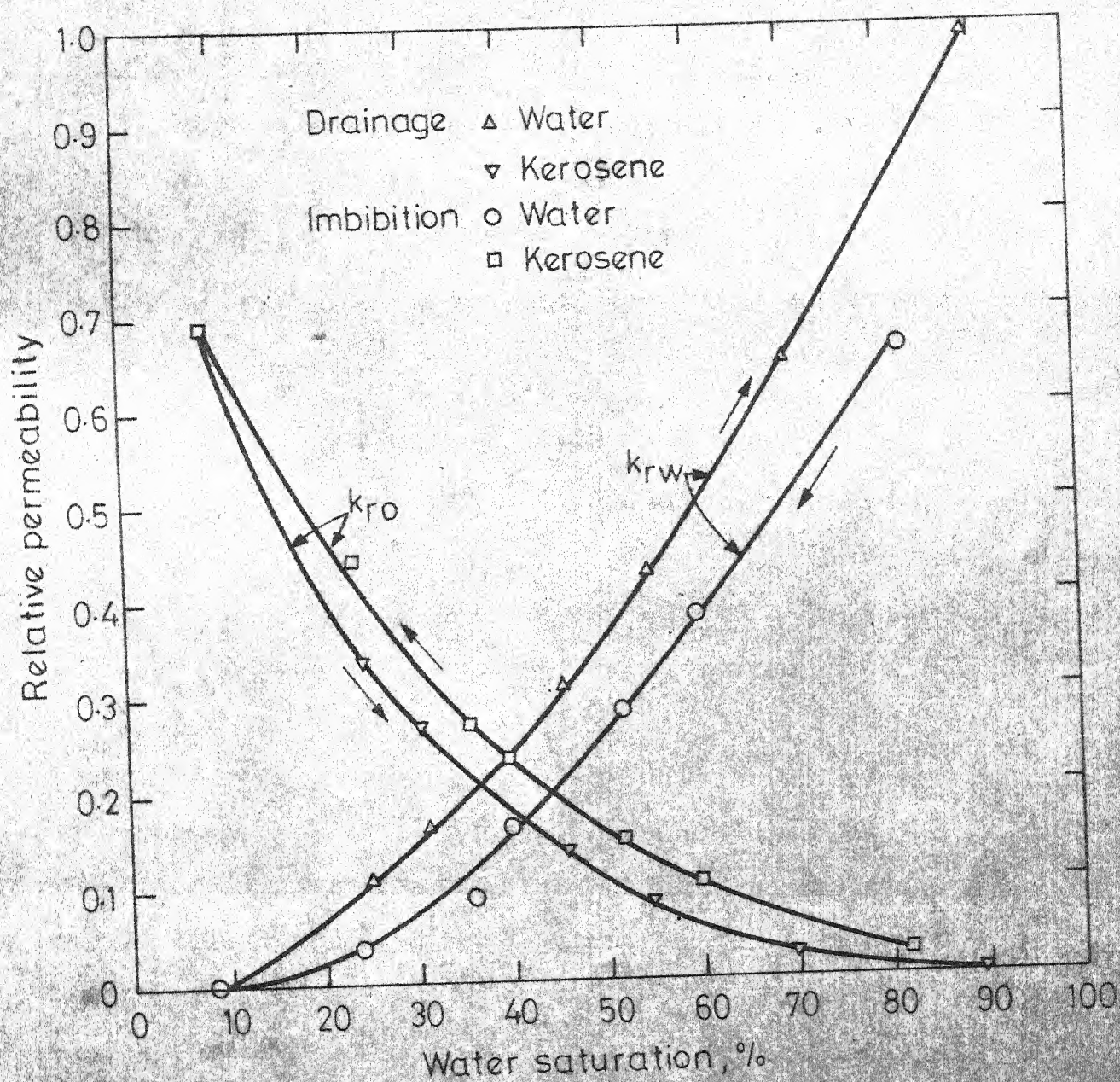


Fig. 8 - Relative permeability vs. water saturation for silicone oil coated glass particles.

was confirmed to be the nonwetting phase by imbibition test. The relative permeability to kerosene phase is less than that to water phase at their respective saturations. This is expected, in this case, as the kerosene phase adheres to the glass beads and forms films and the nonwetting phase water forms bigger channels which make this phase more mobile. As in the case of cleaned glass particles, the relative permeability to water phase at low water saturation is zero and so is the relative permeability to kerosene phase at low kerosene saturation.

Figure 9 shows the relative permeability plotted against the saturation of water added with 100 ppm polyox for cleaned glass particles. The relative permeabilities were calculated with respect to the permeability to distilled water. A comparison with Figure 7 shows the effect of the addition of polyox to water. The relative permeability to water is considerably lowered down by adding polyox. There is also reduction in the relative permeability to kerosene phase. This reduction is a consequence of the adsorption of polymer. However, the reduction in the relative permeability to water phase is a combination of adsorption of polyox and the viscoelastic effect as discussed in the case of single phase flow of dilute polyox solution. Although the relative permeability to kerosene phase decreases, the drastic reduction in the case of polyox solution makes kerosene phase more mobile at all

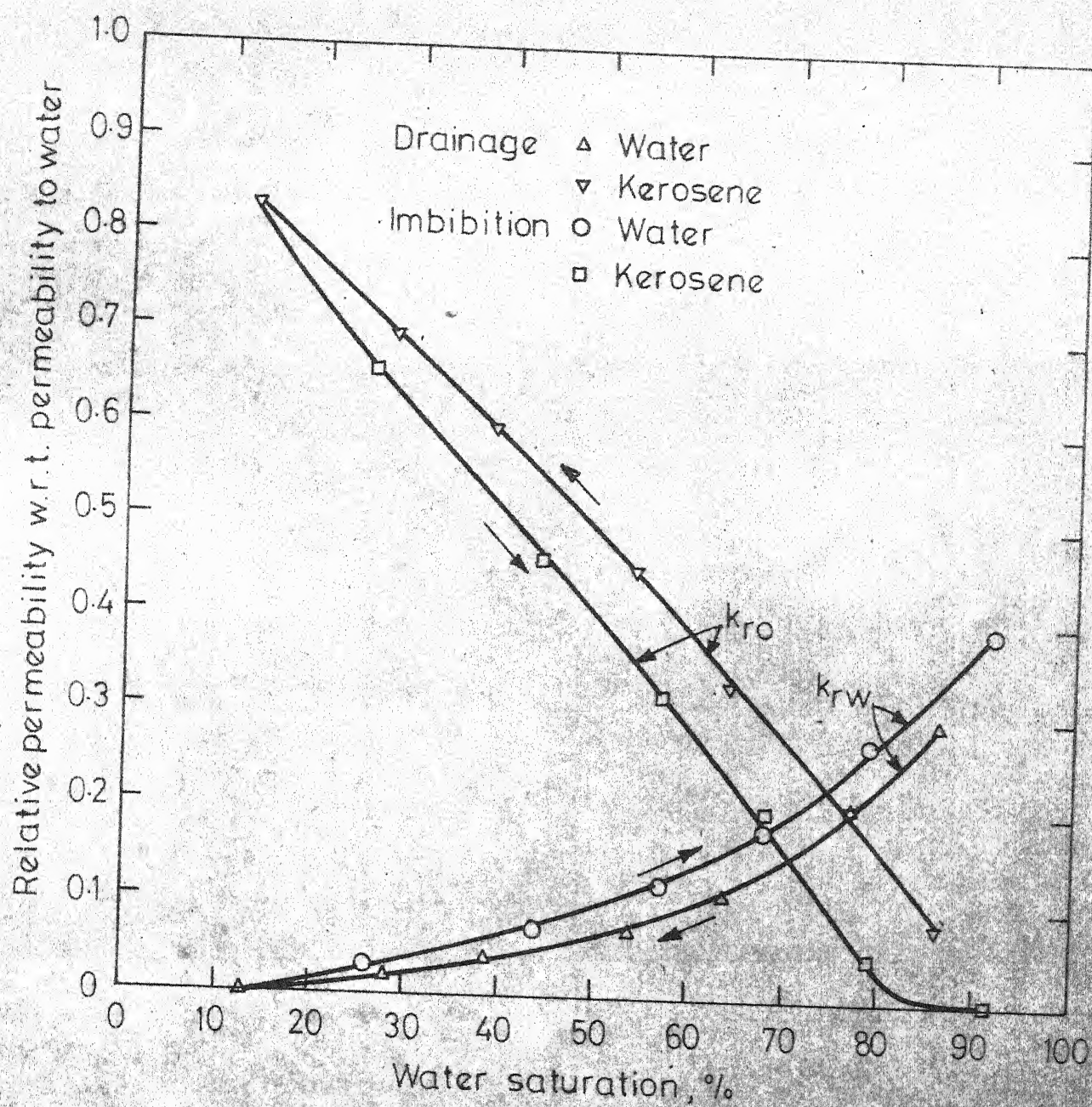


Fig. 9 -Relative permeability vs. saturation of water (with 100 PPM polyox) for glass particles.

the points of saturation. This is clearly shown in Figure 10 where the relative permeabilities are calculated with respect to the permeability to polyox solution. This brings out the reason why polymer flooding is resorted to in secondary oil recoveries. Although relative permeability to both oil and aqueous phase decrease (Figure 6) when polymer is added the ratio k_{ro}/k_{rw} improves significantly which make polymer flooding more efficient. Since the effective viscosity of polymer solution increases several folds in the porous matrix, fingering of water is minimized and more oil is displaced before water breaks through. Polyox solution of higher concentrations are in use (45) since this considerably decreases the relative permeability to the polymer phase, thereby increasing the overall mobility to the oil phase.

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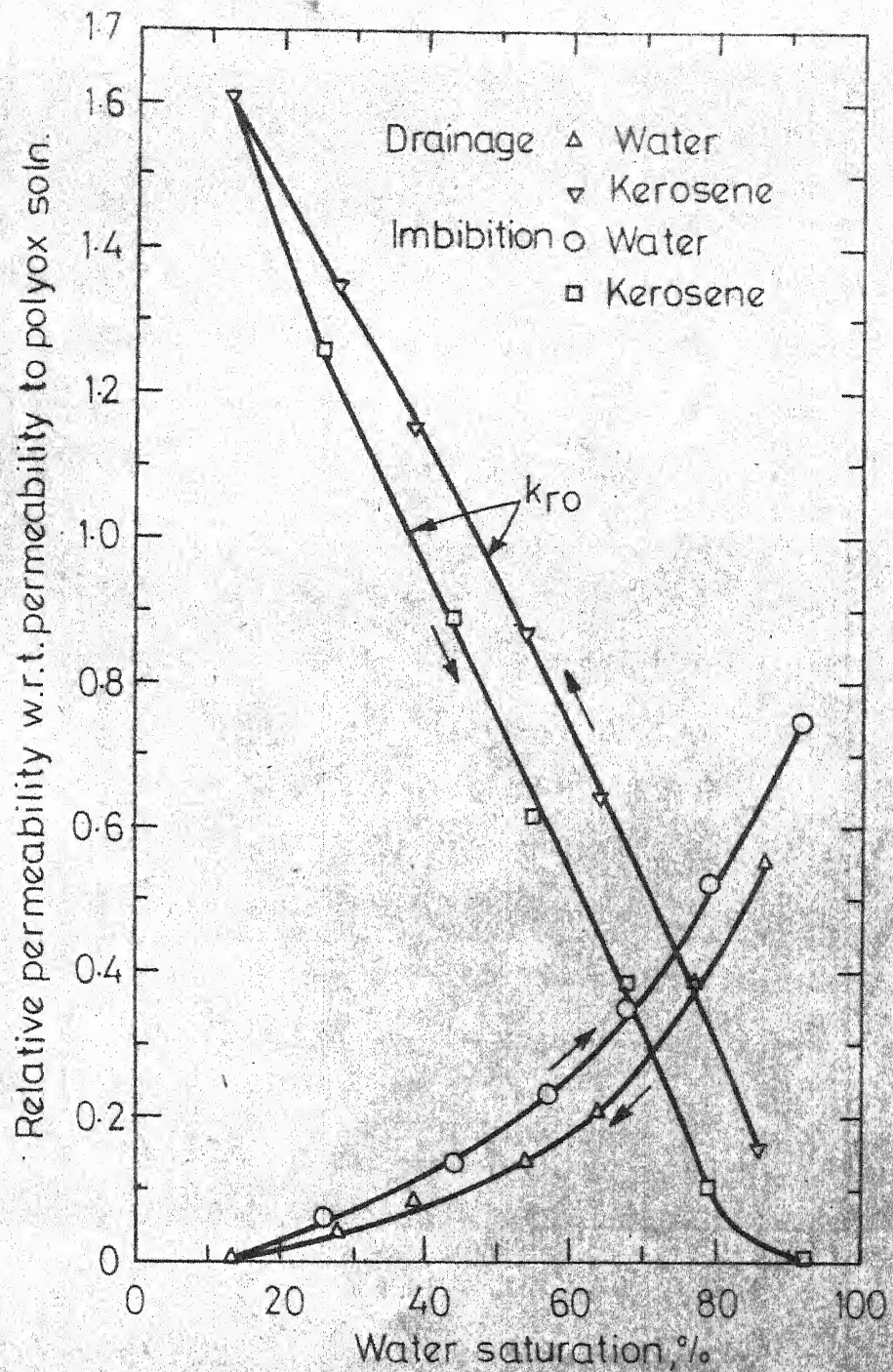


Fig.10 - Relative permeability vs. saturation of water (with 100 PPM polyox) for glass particles.

CHAPTER VI

CONCLUSIONS

1. In the flow of dilute polymer (polyox) solution through packed bed, the pressure drop at any flow rate was found to increase with an increase in the concentration of polyox in water. This increase in pressure drop is attributed to adsorption of polymer and the viscoelastic effects.
2. At low flow rates of the polymer the pressure drop across the packed bed was found to increase linearly with flow rate. However, at high flow rates it was found to fall below the linear relationship due to shear degradation of the polymer.
3. The coating of the glass particles with silicone oil resulted in a decrease in apparent viscosity, suggesting the corresponding decrease in adsorption because of surface alteration.
4. In the flow of water and kerosene through a pack of clean glass beads, which were water-wet, the relative permeability to water phase was lower than that to kerosene phase at their respective saturations.
5. Similarly, the relative permeability to kerosene phase was found to be lower than that to water phase at their respective saturation for a pack of silicone

oil coated glass beads which were water-nonwet.

6. The addition of polyox resulted in reduction of the relative permeability to both the kerosene and water phase. However, the drastic reduction in relative permeability to water phase increased the overall mobility to oil phase at all the points of saturation. This demonstrates the advantage of polymer flooding over water flooding in oil reservoirs.

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CHAPTER VII

RECOMMENDATIONS

1. It is proposed that nuclear magnetic resonance technique be employed to determine saturation in the study of multiple phase flow through porous medium. As has been mentioned, it is preferable to use this technique over others since there are no tracers needed and hence no complications arising from tracer adsorption on the surface. Further, three phase flow studies can be undertaken without any additional equipment for saturation determination.
2. 100 PPM polyox solution was used as an immiscible phase in this present study of twophase flow of fluids through porous media. This investigation should be extended to cover a considerable range of the concentration of polyox solution in order to arrive at the effect of varying polyox concentration on mobility ratio.

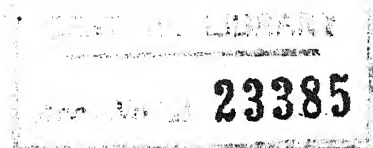
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APPENDIX A

MEASUREMENT OF WETTABILITY

Capillary rise technique (5) (imbibition test) was employed to determine wettability of the glass beads used in the experiment. This method is based on the unopposed penetration of a liquid through a packed bed. The packed bed can be modelled as a bundle of interconnecting and tortuous capillaries of radius, \bar{r} . Washburn equation (64) which applies to flow of a liquid through a single capillary is modified to allow for the tortuous path of the capillaries of a idealized porous medium. The equation then becomes

$$\frac{l^2}{t} = \left(\frac{\bar{r}}{T} \right)^2 \gamma \cos \theta / 2\eta$$

where l is the length of penetration in time, t , γ is the surface tension and η is the viscosity of the liquid, θ is the contact angle, and T is the tortuosity of the bed.

For a given packing of glass beads, the values of \bar{r} and T are constant, hence l^2/t would show a linear relationship dependent only upon the nature of the liquid. This linear relationship does not hold good when liquid rise becomes large enough to cause gravity effect.

The experimental technique for this experiment has been given in Chapter 3.

The results of the penetration of kerosene and water (stock solution used in two phase flow experiments) into a pack

of clean glass beads have been plotted as shown in Figure 11.

The ratio of adhesion tension ($\gamma_o \cos \theta_w$) of water to that of kerosene ($\gamma_o \cos \theta_o$) for clean beads then becomes

$$\frac{A_w}{A_o} = \frac{(l_w^2 / t_w)}{(l_o^2 / t_o)} \frac{\eta_w}{\eta_o}$$

$$\frac{A_w}{A_o} = \frac{21.5}{7.0} \frac{1}{1.97} = 1.56 > 1$$

Here A_w and A_o are adhesion tensions of water and kerosene respectively. Since wetting in a porous medium is a consequence of surface tension and contact angle it is more appropriate to group these two parameters and consider adhesion tension as a measure of wetting. The ratio of A_w and A_o greater than one implies that water is the wetting phase and kerosene nonwetting phase. The displacement of kerosene by water in a packed bed of clean glass beads could not be reproduced because of fingering.

For silicone oil coated glass beads, the contact angle of water with respect to air was inferred to be more than 90° as there was no liquid rise into the packed bed. Kerosene was found to displace water, saturating the bed initially by imbibition.

TABLE - 1

Sl.No.	Solid	Water	Kerosene
1.	Clean glass beads	Wetting phase	Nonwetting phase
2.	Silicone oil coated glass beads	Nonwetting phase	Wetting phase

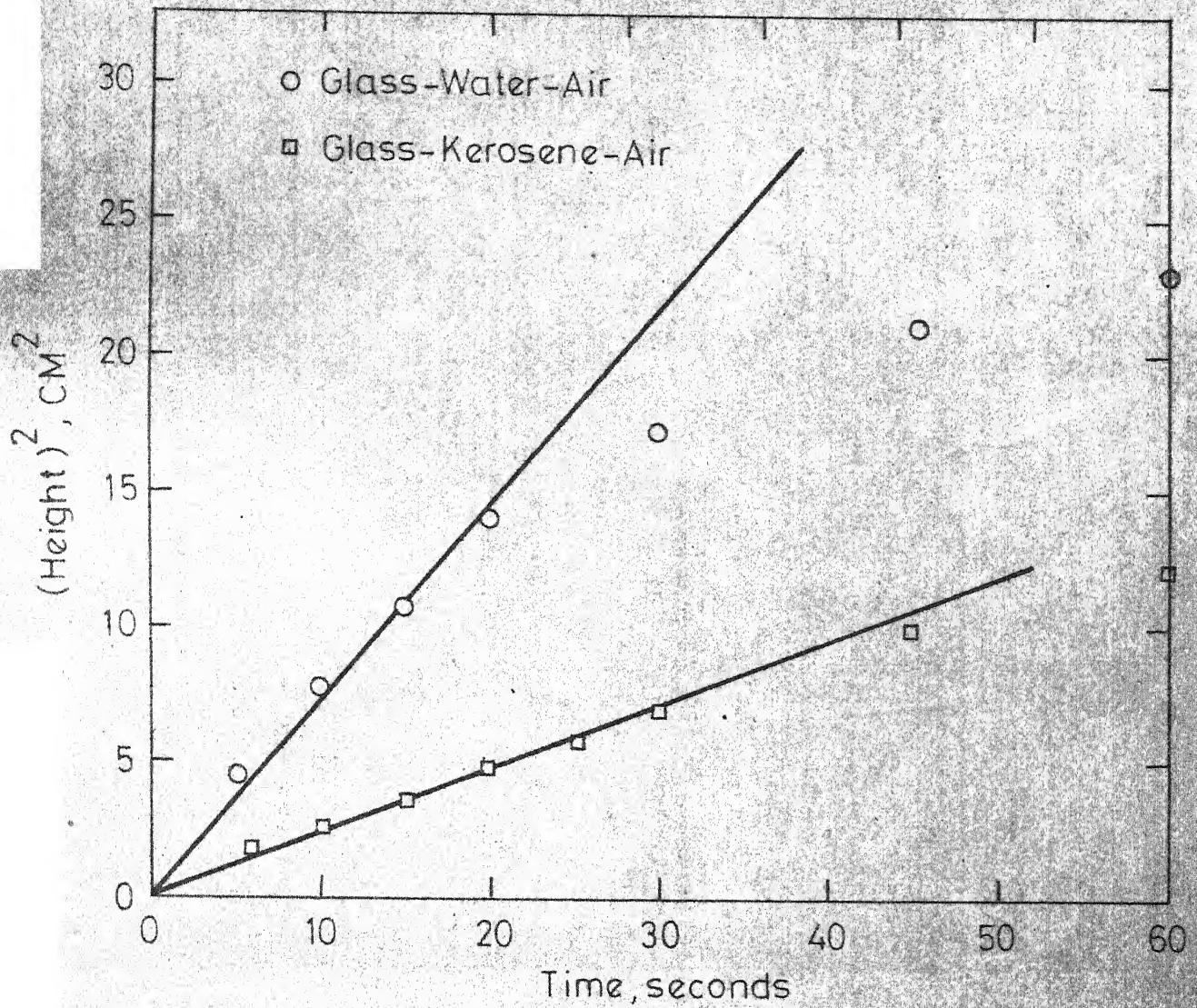


Fig.11 - Wettability measurement plot for clean glass beads.

APPENDIX BTWO PHASE FLOW THROUGH PACKED BED OF CLEAN GLASS BEADSTABLE 2(a)

(a) Water Decreasing:

Sl. No.	q_w ml/min.	q_o ml/min.	ΔP mV	Satn. water %	K_{rw}	K_{ro}
1.	1.25	0.255	43	80	0.4	0.17
2.	0.78	0.875	57	61	0.19	0.42
3.	0.62	1.645	66	45	0.13	0.68
4.	0.42	2.3	77	35	0.075	0.810
5.	0	2.46	67	12	0	0.99

Table 2(b)

(b) Water Increasing

Sl. No.	q_w ml/min.	q_o ml/min.	ΔP mV.	Satn. Water %	K_{rw}	K_{ro}
1.	0.31	1.83	73	26	0.065	0.76
2.	0.75	1.585	80	40	0.13	0.54
3.	1.1	0.679	65	55	0.235	0.355
4.	1.76	0.60	73	65	0.335	0.23
5.	1.84	0.183	55	74	0.46	0.09
6.	2.08	0	39	92	0.74	0.0

Diameter of the packed bed = 1.1 cm.

Length of the packed bed = 24.5 cm.

1 cm. of water = 3.2 mV of the pressure transducer output

Permeability of the porous medium = $10.1 \times 10^{-7} \text{ cm}^2$

Sample Calculation:

For reading no.1, water decreasing

(1)

$$K_w = \frac{q_w \mu_w}{\Delta P_w} \left(\frac{L}{A} \right)$$

The symbols have their usual meaning.

$$K_w = \frac{1.25 \times 1 \times 10^{-2}}{60 \times (43/3.2) \times 981} \times \frac{24.5}{0.95}$$

$$K_w = 4.04 \times 10^{-7} \text{ cm}^2$$

$$\text{So, } K_{rw} = \frac{4.04 \times 10^{-7}}{10.1 \times 10^{-7}} = 0.4$$

(2) Similarly for kerosene phase

$$k_o = \frac{0.255 \times 1.97 \times 10^{-2}}{60 \times (43/3.2) \times 981} \times \frac{24.5}{0.95}$$

$$k_o = 1.72 \times 10^{-7} \text{ cm}^2$$

$$\text{So, } k_{ro} = \frac{1.72 \times 10^{-7}}{10.1 \times 10^{-7}} = 0.17$$

APPENDIX CTWO PHASE FLOW THROUGH PACKED BED OF SILICONE COATED BEADSTABLE 3(a)

(a) Water decreasing

Sl. No.	q_w ml/min.	q_o ml/min.	ΔP mV	Saturation % water	K_{rw}	K_{ro}
1.	1.73	0.04	40	82	0.66	0.03
2.	1.47	0.196	59	60	0.38	0.10
3.	1.06	0.288	57	52	0.28	0.15
4.	0.67	0.50	63	40	0.16	0.235
5.	0.32	0.52	57	36	0.085	0.27
6.	0.18	1.15	78	24	0.035	0.44
7.	0	1.33	58	8.5	0	0.69

b. Water Increasing

Table 3(b)

Sl. No.	q_w ml/min.	q_o ml/min.	ΔP mV.	Saturation % water	K_{rw}	K_{ro}
1.	0.28	0.44	39	25	0.11	0.34
2.	0.43	0.368	41	31	0.16	0.27
3.	0.68	0.153	34	46	0.305	0.135
4.	0.94	0.09	34	55	0.425	0.08
5.	1.27	0.023	30	69.5	0.65	0.03
6.	1.64	0	25	89.5	0.99	0

Permeability of the porous medium = $9.25 \times 10^{-7} \text{ cm}^2$

APPENDIX DFLOW OF WATER (WITH 100 ppm POLYOX) AND KEROSENE
THROUGH PACKED BED OF CLEAN GLASS BEADSTable 4(a)(a) Polymer Solution Decreasing

Sl. No.	q_w ml/min.	q_o ml/min	P mV	Water Satn., %	K_{rw}	K_{ro}
1.	1.15	0.195	66	86	0.29	0.08
2.	0.84	0.502	68	77	0.205	0.20
3.	0.63	1.16	95	64	0.11	0.33
4.	0.36	1.425	86	54	0.07	0.45
5.	0.26	2.38	108	38	0.04	0.595
6.	0.13	2.77	91	28	0.02	0.695
7.	0	2.82	92	13	0	0.83

Table 4(b)(a) Polymer Solution Increasing

Sl. No.	q_w ml/min.	q_o ml/min.	P mV.	Water Satn. %	K_{rw}	K_{ro}
1.	0.14	1.87	78	26	0.03	0.655
2.	0.32	1.295	76	44	0.07	0.46
3.	0.67	1.09	93	57	0.12	0.32
4.	1.07	0.73	99	68	0.18	0.20
5.	1.22	0.15	75	79	0.27	0.045
6.	1.38	0	59	92	0.39	0

Here, the relative permeability has been calculated with respect to the permeability to pure water i.e. $10.1 \times 10^{-7} \text{ cm}^2$. The viscosity of the solution has been taken to be 1.2 cp.

The permeability to polyox solution for clean glass beads is $5.23 \times 10^{-7} \text{ cm}^2$ so when this is taken as a basis for calculating the relative permeability each figure is simply multiplied by 1.93. These results have been plotted in Figure 10.

APPENDIX E

AN EXPRESSION FOR SHEAR RATE IN POROUS MEDIUM

Using the simplest porous media model, a bundle of straight parallel capillaries, it has been shown that (65), the average pore diameter, $\bar{\delta}$, is given by

$$\bar{\delta}^2 = 32T^2 k/\phi \quad (1)$$

Here, the tortuosity factor, T , is the ratio of actual pore length to the length of the porous medium, k is the permeability and ϕ is the porosity of the packed bed.

For a capillary, the average shear rate, Γ , at the wall is given as

$$\Gamma = \frac{8 \bar{V}}{\bar{\delta}} \quad (2)$$

Where \bar{V} is the average rate of advance in the capillary.

For a porous medium

$$\bar{V} = \frac{q}{\phi A} \quad (3)$$

where q is the volumetric flow rate, ϕ is the porosity of the packed bed and A is the cross-sectional area of the bed.

The average rate of advance in a porous medium taking tortuosity into account, then, becomes $T\bar{V}$. Hence the average shear rate, Γ , in a porous medium is given by

$$\Gamma = \frac{8 T \bar{V}}{\bar{\delta}} \quad (4)$$

Combining equations (1) and (4) to eliminate $\bar{\delta}$, the average pore diameter,

$$\Gamma = \frac{\bar{V}}{\left[\frac{1}{2} (k/\phi) \right]^{\frac{1}{2}}} \quad (5)$$

The derivation of this equation has been given by Jennings(49).

The shear rate in porous medium for flow of 100 ppm polyox in water was calculated using this expression which has been plotted in Figure 6.